

## SIMULATION STUDIES OF ENTRY STABILITY AND CONTROL

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## INTRODUCTION

Considerable interest in the problems associated with entry of the X-15 airplane into the atmosphere prompted the early initiation of several simulator programs. Two of these investigations, one by the Ames Laboratory of the NACA (see ref. 1) and the other by North American Aviation (see ref. 2), were for the longitudinal mode only. Primarily the objectives of these two studies were to investigate the longitudinal flying qualities during rapid changes in dynamic pressure, with particular emphasis on the need and requirements of the control system for auxiliary pitch damping, and to investigate the pilot's ability to execute various entry techniques. These programs were followed by a North American modified five-degree-of-freedom study (see ref. 3), which was undertaken with the objective of obtaining initial conditions near an altitude of 200,000 feet for an investigation of reaction controls. However, some interesting results of entry down to the beginning of pullout were obtained also and will be included herein.

## RESULTS AND DISCUSSION

Before presenting the results of these three studies, it is desired to make a few remarks about the simulators. Of perhaps the most interest in the details of the simulators are the flight instruments used and the type of cockpit control. Shown in figure 1 are the pitch-control formation stick and the instrument panel used in the Ames studies. Figure 2 is a photograph of the cockpit of the North American simulator. Both instrument panels, in general, indicated the same quantities with the exception that North American added a sideslip indicator and gyro horizon for their five-degree-of-freedom investigation.

The results of the two studies on the longitudinal mode only will be considered first. Shown in figure 3 are time histories of significant quantities for the design mission of a zero-lift-coefficient entry from 250,000 feet with a 7.33g pullout beginning at an altitude of 117,000 feet.

The aerodynamics used were those of the original X-15 configuration. A number of interesting points can be noted from the data shown in this figure. First, the damping ratio of the unaugmented airplane is low and reaches a peak value of only about 0.03. A second point to be noted is the considerable change in period and the effectiveness of the control in producing normal acceleration during the entry. These changes are due primarily to differences in dynamic pressure  $q$  and static stability of the aircraft. For example, the decrease in the period and the increase in the control sensitivity between the altitudes of 180,000 feet to the beginning of pullout at 117,000 feet is principally the effect of increasing  $q$ . The decrease in control sensitivity and the decreased period which follow reflect the increased static stability at the high angles of attack encountered during the 7.33g pullout. The remainder of these two curves also change in accordance with the decreased stability as the angle of attack is reduced at the end of the recovery to level flight. A third point to be noted is the relatively rapid rate at which the period and control sensitivity change with time. For instance, in just 20 seconds the period reduces from 15 to 6 seconds, while the  $g$ 's per degree of stabilizer incidence ( $g/\delta_h^\circ$ ) change from 0.05 to 0.30. In addition, during the next 15 seconds the period reduces further to 1.4 and back to 2.8 seconds while the sensitivity reduces to 0.15 and then rises quickly to 0.67. Thus, three dynamic characteristics have been shown to occur during entry which may be troublesome to a pilot: those of low damping and large and rapid changes in period and control sensitivity.

Shown in figure 4 are time histories of normal acceleration and stabilizer incidence of an entry in which the pilot's task was to hold an angle of attack of  $20^\circ$  until the normal accelerometer indicated 3.5g, maintain this acceleration until level flight was achieved, and then reduce the normal acceleration to 1 g. The change to monitoring the normal accelerometer occurs at about 100,000 feet. The upper curves are representative of those records when the pilot made no attempt to damp out an oscillation resulting from inadvertent control motions. As is seen from the acceleration record, the pilot was able to maintain the acceleration to approximately 3.5g by ignoring the oscillations of about  $\pm 1$  g. These oscillations, of course, would not compromise the structural integrity of the aircraft but the flying qualities were considered to be unsatisfactory by the pilot. At the center of figure 4 are similar time histories which resulted occasionally when the pilot attempted to damp out any oscillations but instead, as is shown by the stabilizer incidence record, reinforced the motions of the aircraft. The curves shown at the bottom of figure 4 are those with the pitch damper operative. The gain of the pitch damper used here was such as to result in an average damping ratio of 0.3 during the constant  $g$  portion of the pullout. Also, since the maximum stabilizer deflection due to the damper was only slightly over  $1^\circ$ , the control motion is essentially that put in by the pilot. These time histories effectively show that if the pilot is given some artificial damping he has relatively little difficulty controlling the normal acceleration and can easily make a satisfactory entry to level flight.

Shown in figure 5 are some results obtained when various constant gains of the damping feedback loop were tried. For orientation purposes, the present damping requirements of the longitudinal flying qualities specification is shown as the vertical line. For dampers inoperative, this line would move to the left to a damping ratio of approximately 0.1. The dynamic characteristics shown in the figure are those for the angle of attack  $\alpha$  to normal acceleration  $n_z$  type of entry and begin at an altitude of 150,000 feet with the constant 3.5g portion of the entry indicated by the solid line. The curve at the far left is, of course, that of the unaugmented airplane whose dynamic characteristics were considered unsatisfactory by the pilots. The other three curves are for different values of the constant gain of the damping feedback loop which were tried, the first one on the left being that of the augmented damping entry shown in figure 4. Note particularly the wide range of damping ratio during an entry which is the result of holding the gain constant. Now, in general, the pilots would accept the damping given by the lowest gain other than zero, but considered the gain which gave a damping ratio of about 0.6 at the middle of pullout as the best of the three. However, there is some evidence that the pilots would accept much less damping if it were constant during entry. For example, the feedback gain was programmed as a function of altitude so as to give substantially the constant damping ratio of 0.2 with no unfavorable comments by the pilots.

Entry techniques other than the design mission and the constant angle of attack to normal acceleration were tried with dampers operative, such as a constant angle of attack, a constant attitude, or attitude to normal acceleration. Although there was no strong preference for any one type of entry, the pilots did express a mild opinion that it was easiest to monitor attitude. The constant-attitude entry is quite interesting for several reasons. First, attitude information, in contrast to angle of attack, is free from instrument errors due to the low density of the air at high altitudes; in fact, it can be judged reasonably accurately by eye if the horizon is visible. Second, a constant-attitude entry, through its relationship with flight-path angle and angle of attack, automatically programs the angle of attack in such a manner as to result in peak normal accelerations which are not excessive. In order to illustrate this point, in figure 6 are shown three nonpiloted or programmed entries for a zero constant attitude, the differences being due to changes in the initial altitude and velocity. Plotted as the ordinate is the altitude in thousands of feet and plotted as the abscissa is the angle of attack; or, since attitude is zero, the abscissa is also the negative of the flight-path angle. The three entries are: one starting from the design altitude mission of 250,000 feet; one from 142,000 feet, which is comparable to that achieved in the high-speed mission; and one from 428,000 feet. The latter is included since the X-15 is potentially capable of exceeding this altitude. On the three trajectories are marked the peak normal acceleration; the maximum for the design high-altitude mission being only 3.9g whereas that for the extreme altitude is 5.7g,

a value which is well below the limit load factor of 7.33. All these zero-attitude entries will end in mild dives since the flight-path angles are small at the termination of the curves where the normal acceleration is about 1.5g.

As mentioned previously, entry results are to be presented of a modified five-degree-of-freedom study. Since the five degrees of freedom include the lateral mode, the relationship of the dynamic characteristics of an X-15 entry to the lateral-directional damping requirements of the flying qualities specification are shown in figure 7. For comparison purposes, the characteristics of the F-100 airplane flying at 30,000 to 40,000 feet and Mach numbers of 0.6 to 1.3, and those of the X-1B and X-1E airplanes at Mach numbers of 1.26 to 1.58 at 56,000 feet are indicated by the shaded areas. The characteristics of the X-15 below 150,000 feet for the high-altitude, normal-load-factor pullout, design mission are given by the solid curved line. As can be seen, the X-15 exhibits negative to poor damping during the entry, and, at altitudes somewhat above that for initiation of the pullout (which begins at  $|\dot{\phi}|/|v_e| \approx 0.3$ ), the values of the roll coupling parameter  $|\dot{\phi}|/|v_e|$  are high. These large values of the coupling parameter are primarily due to the sizeable magnitude of the effective-dihedral parameter  $C_{l\beta}$ .

Since the objective of this study was to investigate control characteristics at extreme altitudes, certain simplifications in the simulation were made. Among the most important of these were that entry was limited to altitudes above pullout, that entry was constrained to a fixed trajectory by programming dynamic pressure and altitude as a function of time, and that all the aerodynamic derivatives were constant throughout the entire entry with the speed brakes open  $20^\circ$  so as to increase the directional-stability derivative  $C_{n\dot{\beta}}$ . For this condition, the magnitudes

of certain of the derivatives were such that  $6^\circ$  of sideslip or  $5^\circ$  of vertical-stabilizer deflection would give about the same rolling moment as full deflection of the rolling tail, and the roll-to-sideslip ratio was near 6. In addition, as shown in figure 2, the pilots used an instrument display similar in many respects to that identified in the previous paper by Windsor L. Sherman, Stanley Faber, and James B. Whitten as the attitude or more conventional display.

Shown in figure 8 is a time history of a piloted entry from a peak altitude of 250,000 feet, but beginning at 200,000 feet, with initial conditions of a positive rolling velocity of 10 deg/sec and a value of  $\alpha$  and  $\beta$  of  $-10^\circ$ . Plotted as solid curves are the instrument readings of inertial roll angle  $\phi$ ,  $\alpha$ , and  $\beta$  and plotted as dashed curves are the deflections of the rolling tail and the horizontal and vertical stabilizers. Note that in each instance the instrument record and the corresponding time history of the control that the pilot normally deflects

to obtain a change in the reading are placed together. Now the objective of the pilot was to cancel out the initial conditions and then keep the wings level and  $\alpha$  and  $\beta$  zero. The record of this entry shows, however, that the angles of attack and sideslip were small for only a short period of the time, and that the aircraft rolled past vertical to the right and then made more than one revolution to the left. On the record, note how often an angle of sideslip of  $6^\circ$ , which gives the same rolling power as full deflection of the rolling tail, was exceeded. The inability to keep angles of attack, sideslip, and roll small is traceable primarily to this overpowering of the roll control by sideslip. This in turn couples  $\alpha$  and  $\beta$  and makes it extremely difficult for the pilot to control the motions of the aircraft. A secondary effect of the strong coupling also may appear to the pilot as changes in control effectiveness although the aerodynamic derivatives are constant. For example, note that the positive deflection of the horizontal stabilizer at an altitude of about 180,000 feet would appear to the pilot as having an immediate effect in reducing the angle of attack; although,  $3\frac{1}{2}$  seconds later, a similar deflection apparently has no effect. The best technique found in coping with the effect of the large magnitude of  $C_{l\beta}$  was to try to stop the roll first and then reduce  $\beta$  to zero. Some successful flights have been made in this manner, but extremely close attention to the instruments and rapid, precise use of the controls were required.

Shown in figure 9 are two time histories of entry with the same initial conditions as before, but differing in that one is for one-half the normal value of  $C_{l\beta}$  and the other for zero  $C_{l\beta}$ . A comparison of these results with those of figure 8 shows that a reduction in  $C_{l\beta}$  by one-half eased the pilot's task and he was able to keep the rolling and the values of  $\alpha$  and  $\beta$  within reasonable magnitudes until near an altitude of 130,000 feet. As indicated by the solid curves, a further decrease in  $C_{l\beta}$  to zero essentially eliminated the problems of controllability during this portion of the descent. These results have been reflected by the initiation of a North American study of means to reduce substantially  $C_{l\beta}$ . The ease of control with zero  $C_{l\beta}$  and dampers off as exhibited in figure 9, however, does not reflect the difficulties in longitudinal control at the shorter periods and higher dynamic pressures encountered during the pullout.

A comparison of figures 8 and 10 demonstrates the effect of adding dampers about all three axis. The dampers used here gave a damping ratio of about 0.4 in pitch and 0.3 in yaw at 150,000 feet, but since the gain settings were constant their effect varied with altitude. The roll damper provided a similar improvement in the roll characteristics. The primary

advantage of the dampers is that they limit the rates of motion, particularly that of roll, which, as can be seen, gave the pilot adequate control.

The use of dampers raises the question of the authority necessary to accomplish the damping action by the controls. The values used in this study are  $\pm 10^\circ$  for each side of the rolling tail and  $\pm 3^\circ$  for the vertical stabilizer. Since one of the design missions of the X-15 attains a dynamic pressure of 2,500 pounds per square foot, increased importance of the design of the fail-safe features of the dampers is evident.

#### CONCLUDING REMARKS

It has been shown that the original X-15 had the unsatisfactory longitudinal flying qualities of low damping, which is characteristic of aircraft flying at high Mach numbers and high altitudes, and large and rapid changes in period and control sensitivity during pullout, which also adversely affect control. In addition, the X-15 was shown to be difficult to control at altitudes above that of pullout because of the strong coupling between yaw and roll. The reduction of  $C_{l\beta}$  was shown to minimize the coupling, but the favorable simulator results are not completely conclusive since they do not include the pullout. The use of dampers has heretofore been considered somewhat of a luxury for high-speed aircraft, but, in this instance, the addition of damping about all three axes has been demonstrated as almost a necessity to insure consistent and successful entries.

## REFERENCES

1. Matthews, Howard F., and Merrick, Robert B.: A Simulator Study of Some Longitudinal Stability and Control Problems of a Piloted Aircraft in Flights to Extreme Altitude and High Speed. NACA RM A56F07, 1956.
2. Cooper, N., and Zumbrunnen, D.: Analog Simulation Studies of the X-15 Longitudinal Stability and Control Characteristics. Rep. No. NA-56-759, North American Aviation, Inc., July 25, 1956.
3. Cooper, N., and Zumbrunnen, D.: Analog Simulator Studies of the High Altitude Control Characteristics During the Design Altitude Mission of the X-15 Airplane. Rep. No. NA-56-973, North American Aviation, Inc., Sept. 26, 1956.

AMES  
PILOT CONTROL STICK AND INSTRUMENT PANEL

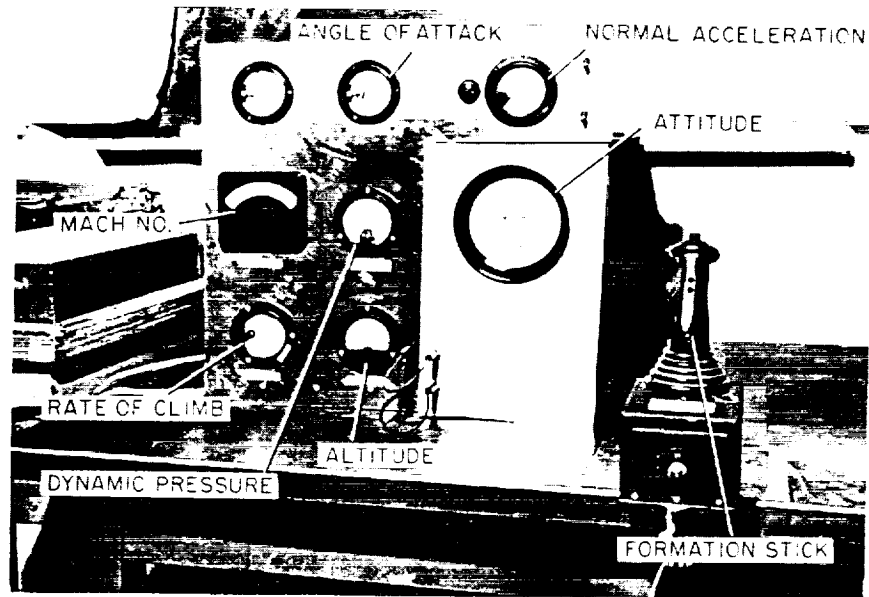


Figure 1

NORTH AMERICAN SIMULATOR COCKPIT

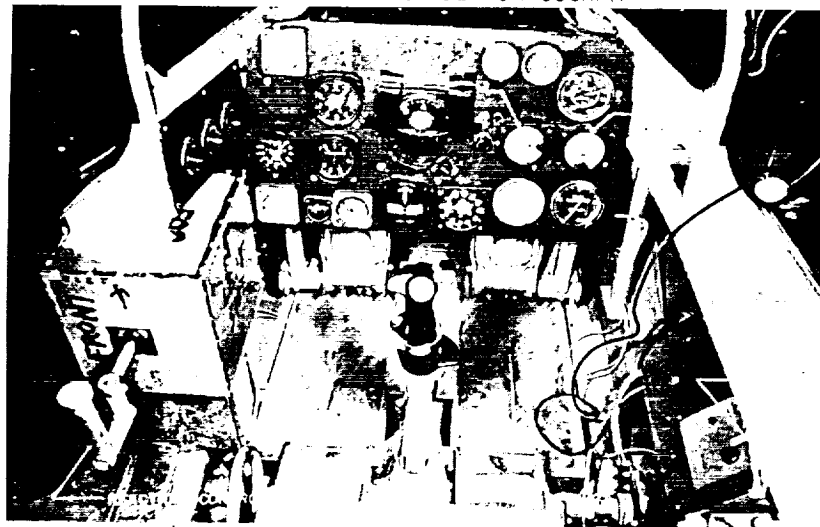


Figure 2

CHARACTERISTICS OF LONGITUDINAL MODE:  
 DESIGN MISSION-BRAKES CLOSED,  $C_L=0$  ENTRY FROM  
 250,000 FT, 7.33 g PULL-OUT INITIATED AT 117,000 FT

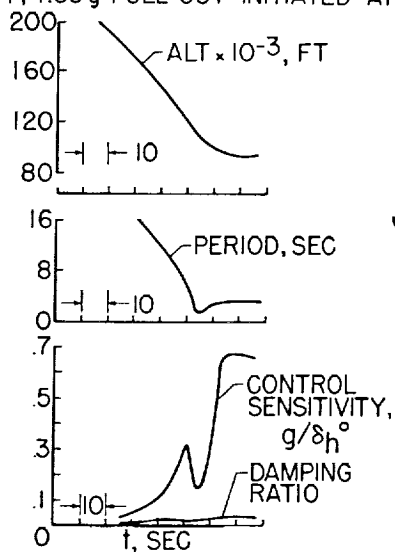


Figure 3

LONGITUDINAL OSCILLATIONS DURING ENTRY  
 $\alpha = 20^\circ$  TO  $n_z = 3.5g$  ENTRY

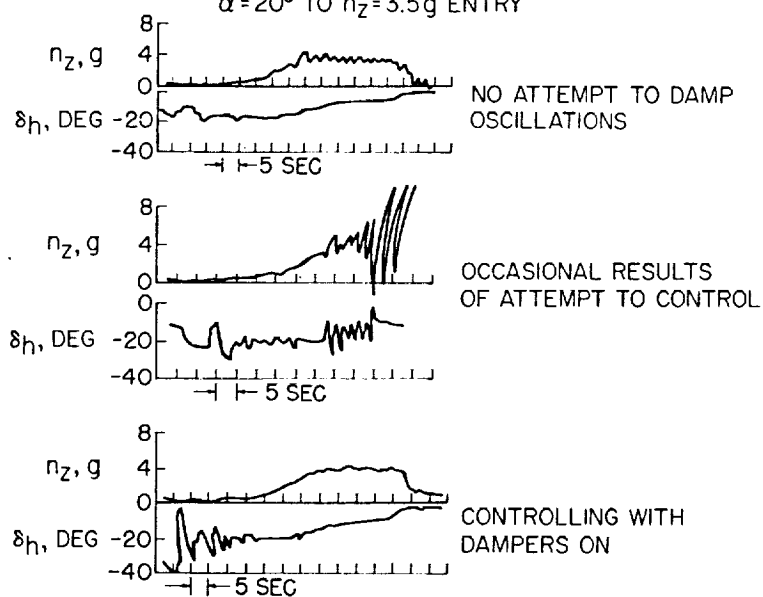


Figure 4

SCOPE OF DAMPER INVESTIGATION  
 $\alpha = 20^\circ$  TO  $n_z = 3.5$  g ENTRY

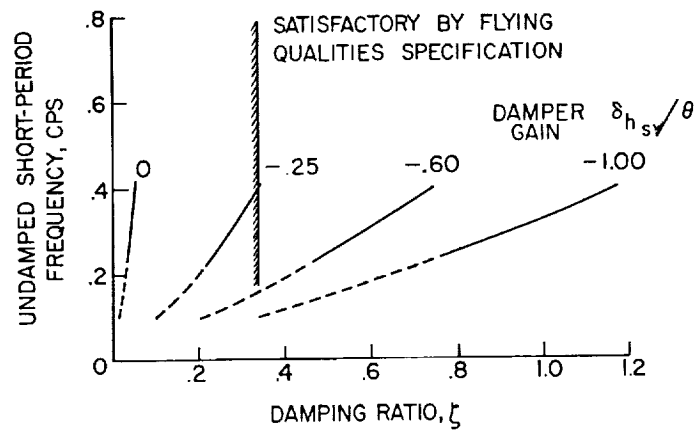


Figure 5

CHARACTERISTICS OF PROGRAMMED  
 ZERO  $\theta$  ENTRIES; BRAKES CLOSED

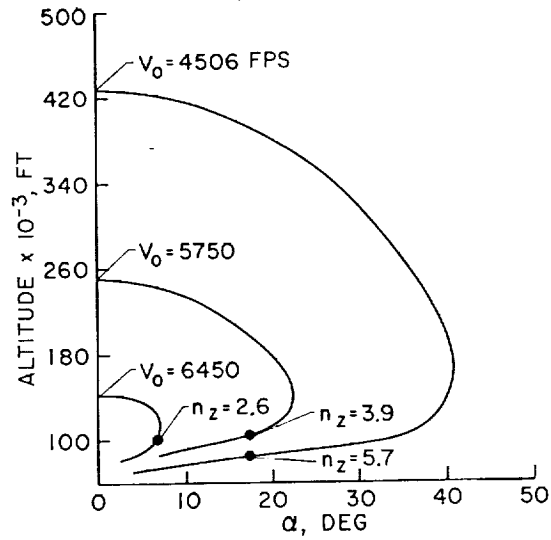


Figure 6

# COMPARISON OF LATERAL-DIRECTIONAL DAMPING CHARACTERISTICS WITH FLYING QUALITIES SPECIFICATIONS

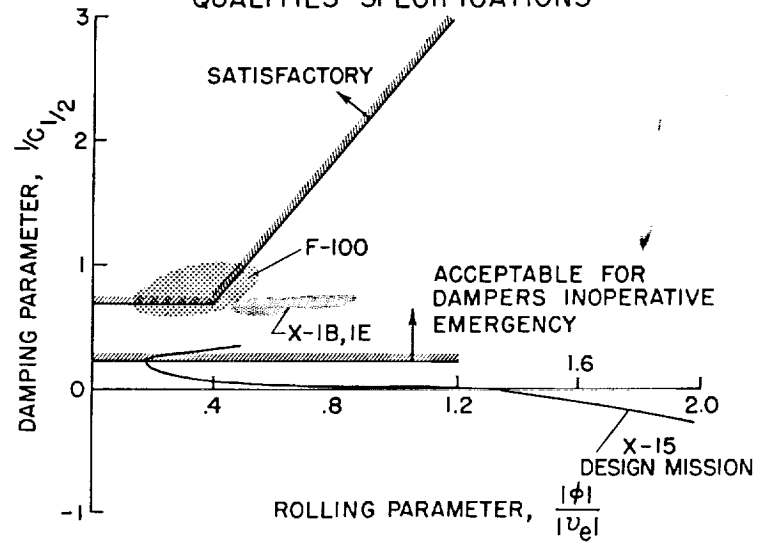


Figure 7

## ENTRY WITH DAMPERS OFF, NORMAL $C_{1\beta}$

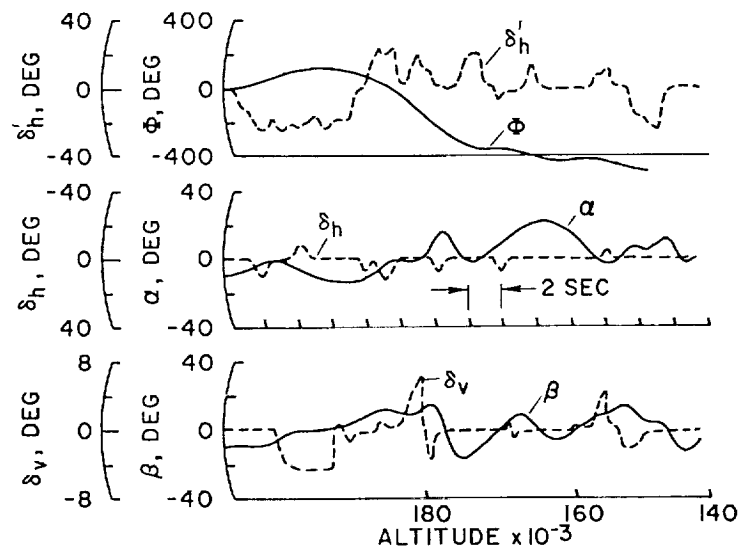


Figure 8

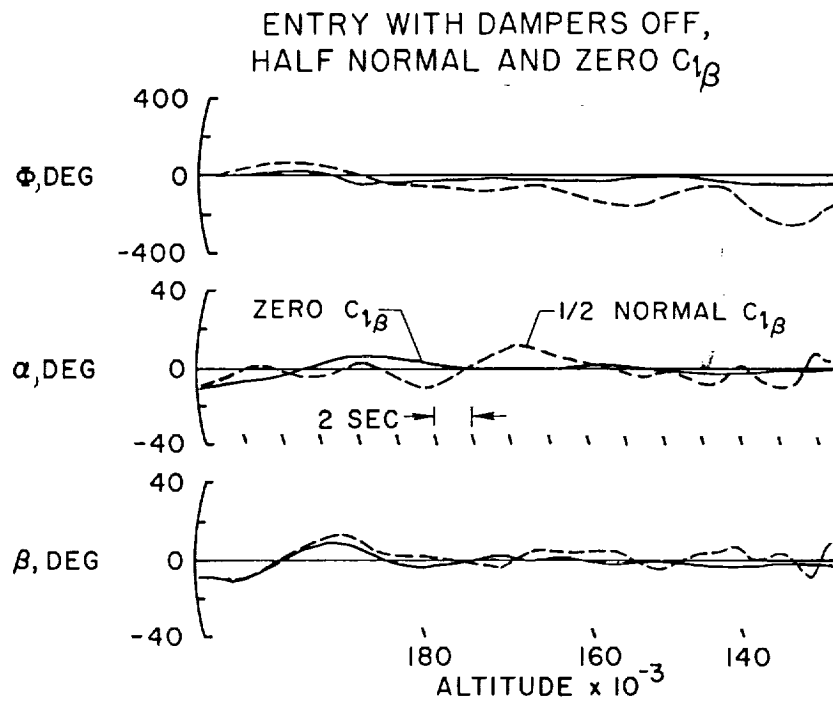


Figure 9

ENTRY WITH DAMPERS OPERATIVE, NORMAL  $C_{1\beta}$

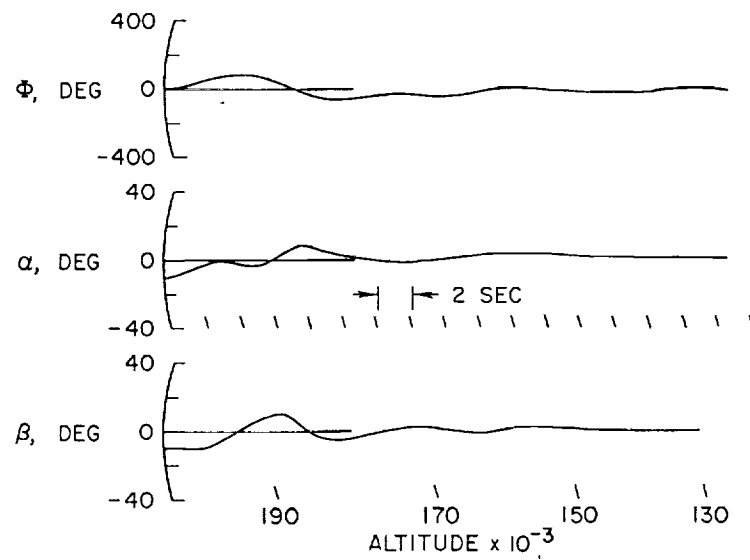


Figure 10